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Gravitational Star Formation Thresholds and Gas Density in Three Galaxies

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It has long been held that the star formation rate (SFR) may be described as a power law of the gas density, ρ^n, as given by Schmidt (1959). However, this relation has as yet remained poorly defined and is likewise poorly understood. In particular, most studies have been investigations of global gas and star formation properties of galaxies, due to lack of adequate high-resolution data for detailed studies of individual galaxies. The three spiral galaxies in this study have published maps of both H_2 (as traced by CO), and HI, thereby enabling us to investigate the relationship between total gas surface density and SFR.

Threshold gas densities below which massive star formation is suppressed in spiral galaxies were suggested early on by Quirk (1972), and evidence for such behavior has been presented by several recent authors. These preliminary reports lack detail, and consider only atomic HI gas. In addition, Kennicutt (1989) demonstrates strong evidence for thresholds in azimuthally-averaged, total (H_2 + HI) surface gas densities, based on the gravitational stability considerations suggested by Quirk. In Kennicutt's paper, Quirk's critical threshold gas density is given as a surface density by

$$\Sigma_c = \alpha \frac{\kappa c}{3.36 G}$$

This expression was derived directly from the gravitational stability criterion for a thin disk of gas embedded in stars (Toomre 1964, Cowie 1981), where c is the gas velocity dispersion, and κ is the epicyclic frequency. In that study, Kennicutt empirically determined α, the dimensionless "stability parameter", to have a value near 0.7 for an assumed $c = 6\,\mathrm{km\,s^{-1}}$.

The purpose of the present investigation is the comparison of spatially-resolved total surface gas density in three galaxies (NGC 6946, M51, and M83) to Σ_c as given by the above model. CO, HI, and Hα data for NGC 6946 were taken from Tacconi-Garman (1988), and for M51 and M83 from Lord (1987). We used a CO-H_2 conversion of $N(H_2)/I_{CO} \cos i = 2.8 \times 10^{20}$ atoms $\mathrm{cm^{-2}/(K\,km\,s^{-1})}$, and summed the H_2 and HI data for each galaxy to obtain the total hydrogen gas density. This total was then multiplied by a factor of 1.36 to include the contribution of helium to the total surface gas density. We assumed distances to NGC 6946, M51, and M83 to be 6.0, 9.6, and 8.9 Mpc respectively, with inclination angles of 30, 20, and 26°. Hα flux was used as the measure of SFR for NGC 6946, and SFR for the remaining two galaxies was taken directly from Lord as computed from Hα measurements.

Figure 1a-c shows the total density as a function of radius for each galaxy, with the threshold density Σ_c indicated by the broken line. Figure 2 shows the Hα flux as a function of density for NGC 6946, with specific radii plotted with different symbols so that a single value for Σ_c applies to each data set, as indicated by the different lines. The remaining two galaxies show behavior similar to NGC 6946 in SFR vs. Σ. The results in Fig. 1 show a remarkable correlation between the total gas density and the threshold densities given by the gravitational stability criterion. In particular, the threshold density appears to define a lower limit to the gas densities. As a result, Fig. 2 does not indicate

the steep, nonlinear drop in SFR for densities below Σ_c which would be expected in the threshold model. Since none of the points in question are significantly below the threshold density beyond the range of errors, and considering that all the data lie well within the star-forming disks, it may not be surprising that all points exhibit star formation. It is also quite possible that the 45" mapping resolution of the hydrogen densities is not good enough to effectively isolate low-density regions below the threshold.

That the gas density should follow the threshold so closely would be logical in light of gas depletion by star formation. If star formation requires a threshold gas density, one would expect that after several characteristic star-forming time scales, the gas would be depleted to the level of the threshold. Thus the near coincidence of the gas density with the threshold in itself supports such a model. The noteworthy result here is the fact that the threshold marks a *lower* boundary to the gas, instead of an upper one, as would be expected from such a scenario. This observation may perhaps be understood in terms of gas infall models, or feedback mechanisms between the SFR and threshold density. It may also be that the observed Σ_c as a lower bound to the gas density is evidence of a threshold for molecular cloud formation, instead of star formation per se (Cowie 1981, Elmegreen 1979). There are several possibilities, and our result may prove to be a criterion in determining appropriate models for gas dynamics and star formation.

Likewise, we must bear in mind that the present study is preliminary in nature. There are many physical conditions for which gas density would follow a 1/R law, as does Σ_c (*e.g.* Struck-Marcell 1989, Wyse and Silk 1989). Also, if α in our study is in error by more than a factor of about 1.5, the threshold density will no longer neatly mark a lower boundary to the gas density. One should note however, that Kennicutt (1989) finds at most a 25% deviation in α for his sample. Hence we wish to emphasize that our result is fairly robust, and we are astonished to find that all three galaxies agree so well in the qualitative pattern.

The results of these full-disk studies thus show a remarkable correlation between the total gas density and the threshold densities given by the gravitational stability criterion. In particular, the threshold density appears to mark a lower boundary to the range of gas densities in these galaxies, which may have consequence in determining appropriate models for star formation and gas dynamics. More evidence is required to verify this result, and we are currently undertaking a high-resolution study of the nearby spiral M33 and other galaxies to further investigate this problem.

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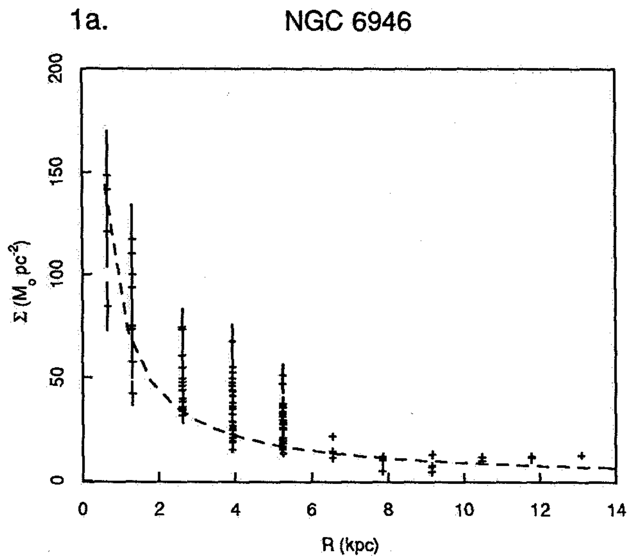

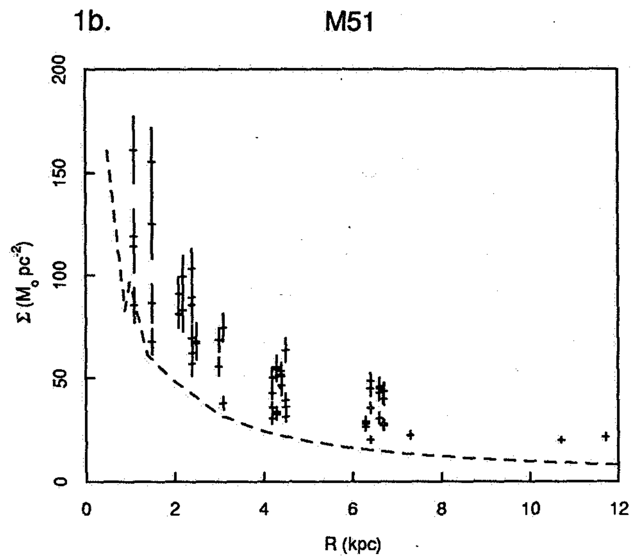

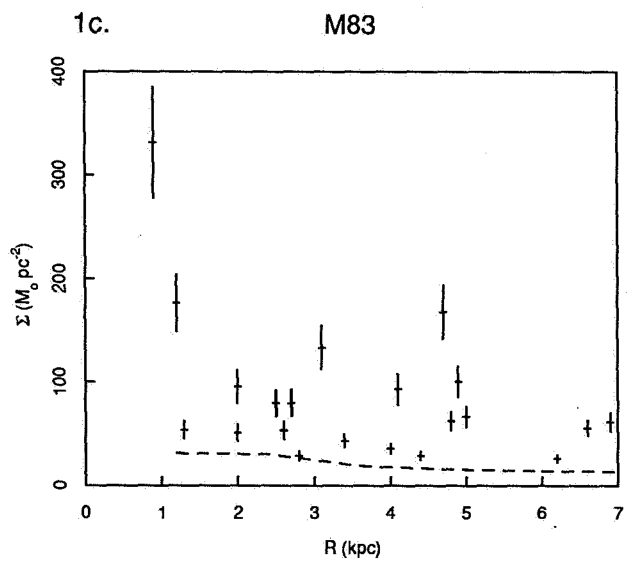

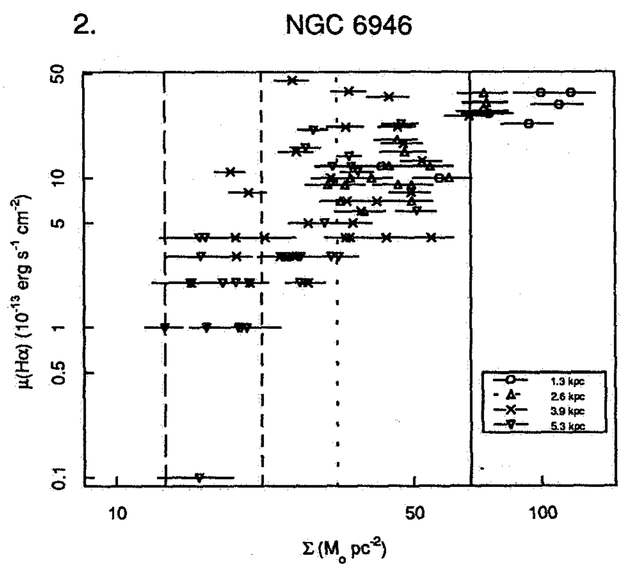

Fig. 1. Total surface density vs. radius for each galaxy. The threshold density Σ_c is indicated by the broken line.

Fig. 2. Hα surface flux density per 45" beam vs. total surface density, for selected radii of NGC 6946. Different symbols indicate points at different radii, with corresponding thresholds as indicated by different line types in the legend. The point at μ(Hα)=0.1 is actually a zero detection.